Analysis of CubeSat Reliability

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Introduction and Motivation

- CubeSat reliability (and by extension, constellation reliability) is a key parameter informing the design of the constellation
  - Trade-off for the number of CubeSats in a constellation vs the reliability of each individual CubeSat
- A quantitative assessments of CubeSat constellation reliability was developed based on multiple databases of historical performance
  - Databases and reliability models are now sufficiently mature to produce useful statistics

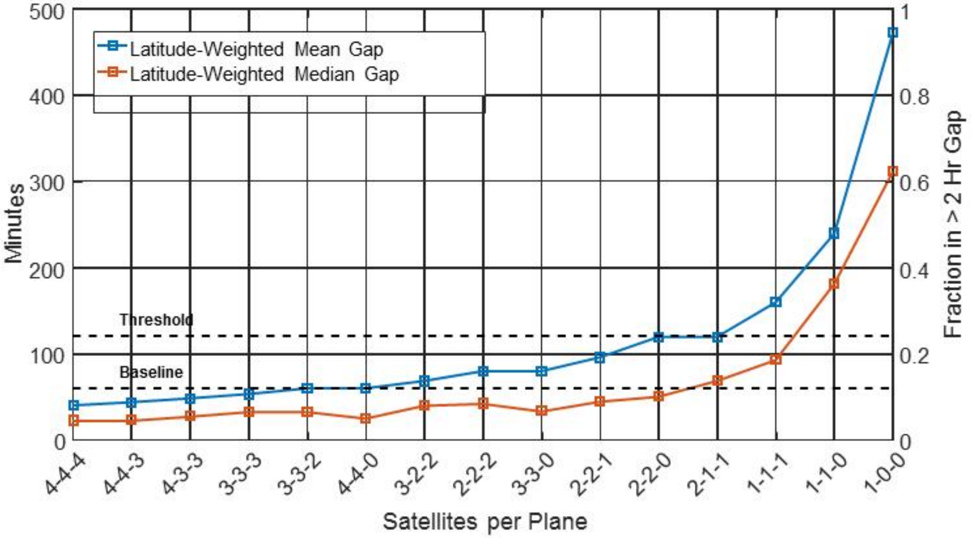
Outline

- Review of Science Performance
- Overview of CubeSat Failure Models
- Simulation Approach and Tailoring for this Analysis
- Mathematical Implementation Details
- Results
- Summary

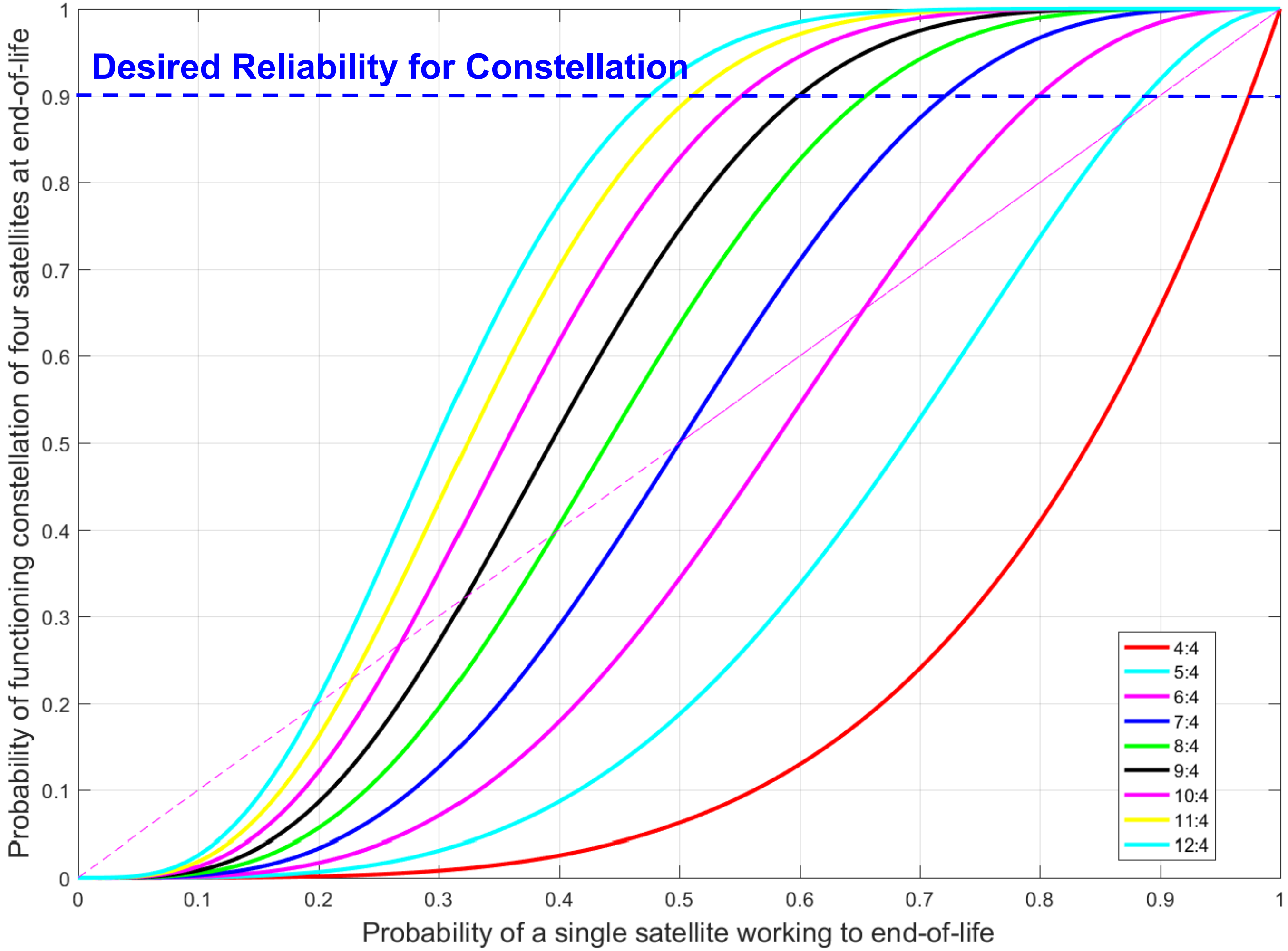
Science Performance vs. Constellation Size

- **Median revisit requirement: 1 hour (baseline), 2 hour (threshold)**
  - **Four satellites meet baseline revisit requirement**
  - **Three satellites meet threshold revisit requirement**

- **Strategy: Maximize probability of meeting *baseline* requirements**
  - **Maximize probability of at least four satellites operating concurrently though 18-month mission life**



Constellation Reliability versus Single Sat Reliability



Outline

- Review of Science Performance
- **Overview of CubeSat Failure Models**
- Simulation Approach and Tailoring for TROPICS
- Mathematical Implementation Details
- Results (TROPICS Project & NASA/ESSP)
- Summary

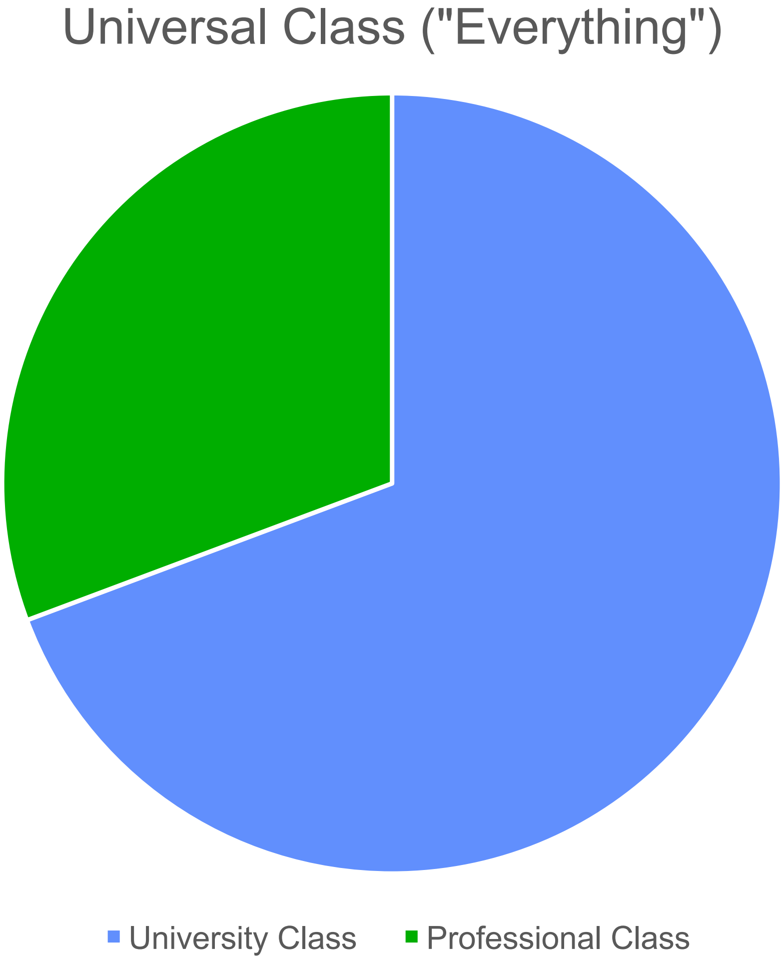
Overview of CubeSat Failure Modeling

- There has been an energetic sector of recent CubeSat research devoted to failure database development, parametric modeling, and statistical analyses
  - **"Munich Model":** M. Langer and J. Bouwmeester, "Reliability of CubeSats – Statistical Data, Developers' Beliefs and the Way Forward," 30th Annual AIAA/USU Conference on Small Satellites, 2016.
  - **Swartwout Database and Analysis:** https://sites.google.com/a/slu.edu/swartwout/home/cubesat-database
  - **G. Richardson**, K. Schmitt, M. Covert, and C. Rogers, 2015, "Small Satellite Trends 2009-2013," Proceedings of the AIAA/USU Conference on Small Satellites, Technical Session VII: Opportunities, Trends and Initiatives, SSC15-VII-3, http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3212&context=smallsat.

Some Distinctions and Observations

- Munich model has R(t), but lumps all satellites together into a “universal class”
- Swartwout database does not have R(t), only R(90th day), but breaks up the data in many useful quantitative ways (e.g. subdivision of “university” and “professional” class builds)
  - Shows failures dominated by bus, not payload (86% bus)
  - “University class” CubeSat failures occur more frequently by a factor of 23/8 relative to “professional class” CubeSat failures
- Richardson analysis identifies “fly-learn-refly” as the single most dominant predictor of CubeSat reliability and cites quantitative statistical improvement for up to five cycles
- 2016 NRC CubeSat report (“Thinking Inside the Box”) makes two interesting statements:
  - Historical success rate of NASA Class C/D missions is ~80% (Class A/B is ~90%)
  - CubeSat failure rate halved in the last eight years (“maturation effect”)

Breakdown of CubeSat Classes



Simulation Approach

- Use a hybridization of the Munich and Swartout models and make adjustments to predict the reliability of:
  - Originally proposed 12-satellite "universal class" constellation
  - Currently proposed 6-satellite "professional class" constellation

- Assume four satellites are needed for 18 months to claim baseline science success for either scenario

- Adjustments:
  - "Maturation effect" (Across-the board-improvement in CubeSat reliability in 2017 relative to database completed in 2014)
  - Additional fly-learn-refly cycles
  - "Universal" vs "Professional" class

"Universal Class" = University + Professional

Implementation Notes

- “Maturation” adjustment
  - Conservatively assume that future improvements will yield a halving of failure rate in 12 years (not 8). Thus failure reduction from 2014 to 2017 is 0.5^(3/12) = 0.84.
- Fly-learn-refly adjustment
  - Swartwout statistics show a failure reduction ranging from approximately 0.6 to 0.7 over the course of five cycles. Conservatively choose 0.75 as the failure reduction factor for all cycles up to five.
  - Relative to baseline Munich database, assume one additional cycle for payload maturity and three additional cycles for bus maturity.
- “Professional” class adjustment
  - To convert Munich “total” population to “professional” population, we need to know relative amount of each population (79/35 for u/p) and the ratio of failure rates (23/8 for u/p), thus:
  - Failure reduction factor = (79+35)/(79*23/8 + 35) = 0.43

Implementation Notes (Continued)

- “Maturation” adjustment = 0.84
  - At the 90th day, 84% fewer failures than before

- Fly-learn-refly adjustment = 0.75 per cycle
  - At the 90th day, 75% fewer failures than before for one cycle
  - At the 90th day, 42% fewer failures than before for three cycles

- “Professional” class adjustment = 0.43
  - At the 90th day, 43% fewer failures than before

Adjustment of the Wiebull Parameters

- **All Wiebull parameters are updated with each adjustment.**
- **The Wiebull parameters are all scaled by the same single multiplicative factor to achieve the desired failure adjustment at the 90th day to be consistent with Munich model.**
- **This has the effect of narrowing the R(t) distribution as reliability improves (consistent with Langer, Figure 14, for example).**

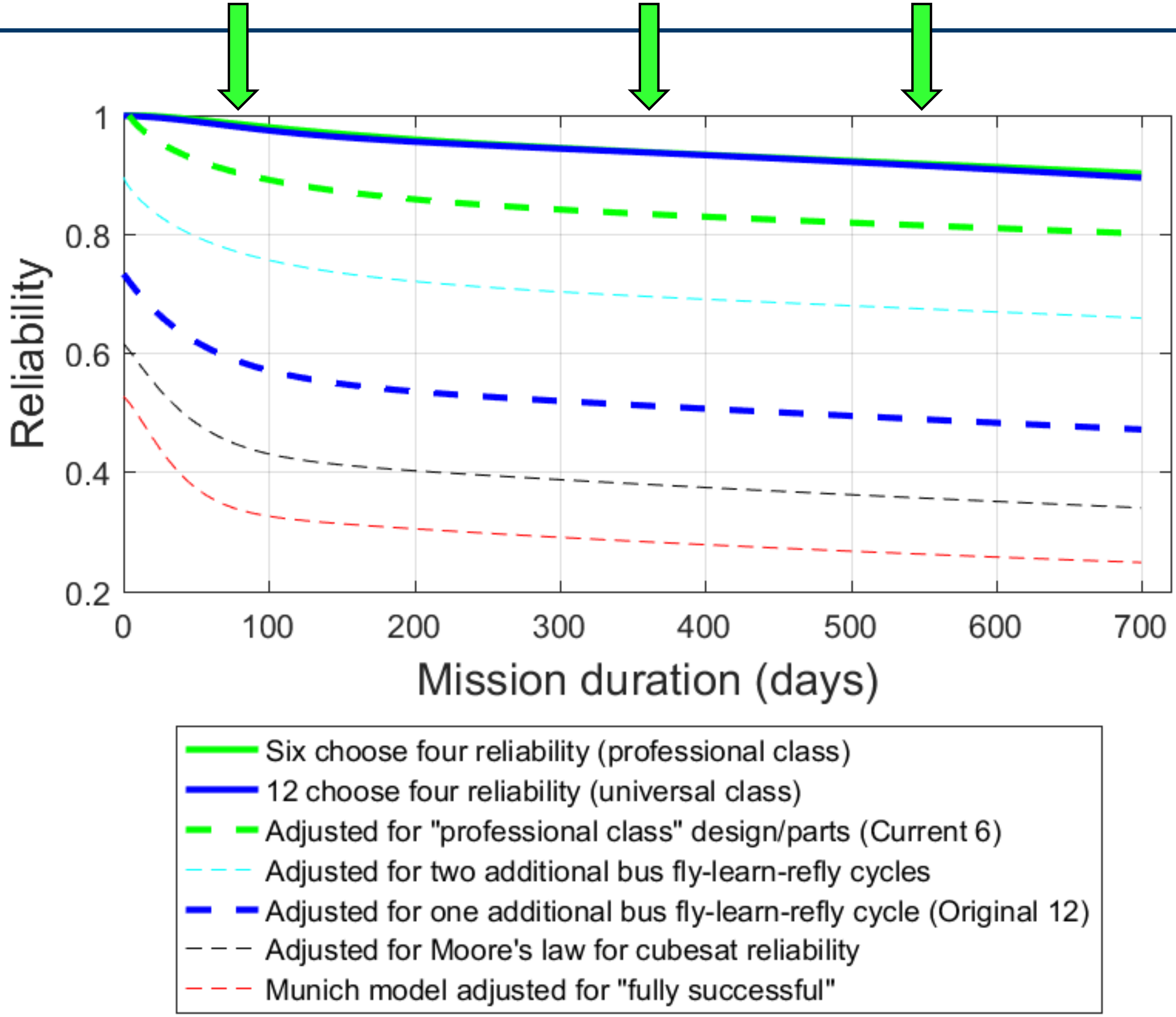
Summary of Results

- Original 12-sat constellation of “Universal” class:
  - Add adjustment for failure reduction due to CubeSat maturation
  - Add adjustment for one additional fly-learn-refly cycle
  - Results: single-sat reliability at 18 months: 0.49, 12/4 constellation reliability at 18 months: 0.9165

- Upgraded 6-sat constellation with “Professional” class bus:
  - Add adjustment for failure reduction due to CubeSat maturation
  - Add adjustment for three additional fly-learn-refly cycles
  - Add adjustment for “professional” class CubeSat design and parts
  - Results: single-sat reliability at 18 months: 0.82, 6/4 constellation reliability at 18 months: 0.9194

- Curves on next chart

Plot of Results



Solid lines: Probability that four vehicles from the constellation survive for a given time

Dashed lines: Probability that a single vehicle survives for a given time

Summary

- Results indicate a higher probability of baseline mission success for the upgraded 6-CubeSat constellation relative to the “as proposed” 12-CubeSat constellation

- Results indicate >90% probability of baseline mission success for the current 6-CubeSat constellation

Reliability of 6 “professional” CubeSats > reliability of 12 “university” CubeSats

Backup Data

Munich Model

- M. Langer and J. Bouwmeester, "Reliability of CubeSats – Statistical Data, Developers' Beliefs and the Way Forward," 30th Annual AIAA/USU Conference on Small Satellites, 2016.
- "CubeSat Failure Database" of 178 CubeSats, latest launch date of June 30, 2014
- Percent Non-Zero (PNZ) to handle DOA cases
- 2-Wiebull mixture function with seven parameters:

$$\boldsymbol{P(t) = PNZ\left\{\alpha_1 exp\left[-\left(\frac{t}{\theta_1}\right)^{\beta_1}\right] + \alpha_2 exp\left[-\left(\frac{t}{\theta_2}\right)^{\beta_2}\right]\right\}}$$